GEOLOGIC MAP OF THE WESTERN EQUATORIAL REGION OF MARS

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DESCRIPTION OF MAP UNITS

Although the origin and composition of many units are obscure or controversial, their interpretations are based on objective descriptions of morphologic characteristics visible on Viking photomosaics and images.

LOWLAND TERRAIN MATERIALS

Consist of all plains-forming units between the highland-lowland boundary scarp and the north edge of the map area, exclusive of materials of the western volcanic assemblage on the Tharsis swell.

Northern plains assemblage

Materials deposited in widespread sheets on northern plains. Within each formation, members mapped at places on basis of crater density; these contacts are approximately located. Assemblage postdates highland-lowland boundary scarp (Scott, 1979).

ARCADIA FORMATION—Forms low-lying plains in Arcadia, Amazonis, and Acidalia Planitiae. Embays highland margins and partly buries outflow channels of Kasei, Shalbatana, Simud, Tiu, and Ares Valles. Members distinguished on basis of morphology, albedo, and crater density; common boundaries of older members mapped arbitrarily at places. Flows with lobate margins and small hills with summit craters visible in many places. High-resolution pictures show that sources of some flows are small cratered cones. *Interpretation:* Mostly lava flows and small volcanoes

Aa5 Member 5—Relatively small areal extent. Dark, fresh-appearing flows; few superposed impact craters. Type area: lat 47° N., long 30°

Aa4 Member 4—In Arcadia Planitia underlies member 5 and has similar appearance; one other occurrence in channel system of Chryse Planitia. Type area: lat 45° N., long 175°

Aa3 Member 3—Forms smooth plains west of Olympus Mons aureoles; embays both the aureoles and fractured terra of Acheron Fossae. Flow fronts visible in places. Type area: lat 15° N., long 155°

Aa2 Member 2—Underlies members 3, 4, and 5 in Arcadia Planitia. Includes many small (<10-km-diameter) structures resembling volcanoes and cinder cones. Curved concentric ridges visible on surfaces of flows. Type area: lat 45° N., long 155°

Aa1 Member l—Widespread in Chryse and Amazonis Planitiae. Mare-type (wrinkle) ridges common. Type area: lat 30° N., long 40°

MEDUSAE FOSSAE FORMATION—Consists of extensive, relatively flat sheets, generally smooth to grooved and gently undulating; deposits appear to vary from soft to indurated; albedo moderate. Occurs near equator in western part of map area. Total thickness may exceed 3 km

Amu Upper member—Discontinuous but widespread deposits extend from south of Olympus Mons westward across Amazonis Sulci to map boundary. Smooth, flat to rolling, light-colored surfaces; sculptured into ridges and grooves in places (as in Medusae Fossae); broadly curved margins, locally serrated. Type area: lat 0° N., long 160°. *Interpretation:* Nonwelded ash-flow or ash-fall tuff or thick accumulation of eolian debris; wind eroded, particularly along margins

Amm Middle member—Similar to upper member but in places (as at Memnonia Sulci) surface appears rougher, more deeply eroded; cut by scarps of Gordii Dorsum and transected in type area by intersecting joint sets. Type area: lat 10° N., long 160°. *Interpretation:* Welded and nonwelded pyroclastic rocks or layers of relatively soft to indurated eolian deposits

Aml Lower member—Two small occurrences in western map area. Surfaces smooth to rough and highly eroded, darker than those of other members. Type area: lat 0° N., long 174°. *Interpretation:* Lava flows interbedded with pyroclastic rocks or eolian deposits

VASTITAS BOREALIS FORMATION Subpolar plains deposits of northern lowlands. Its four members distinguished on basis of morphology or albedo contrast; placement of contacts locally arbitrary

Hvm Mottled member—Major occurrence north of map boundary (Tanaka and Scott, unpub. data, 1985); extends as far south as topographic reentrants between Acidalia and Chryse Planitiae where appears windswept. Crater-ejecta blankets have higher albedo than adjacent terrain; lobate flow fronts visible; some small hills present. Type area: lat 55° N., long 40°. *Interpretation:* Possibly consists of lava flows erupted from fissures and small volcanoes or of alluvial and eolian deposits. Mottled appearance due to contrast between generally low albedo of plains and brightness of small hills and impact-crater aprons

Hvg Grooved member—Similar to mottled member in Acidalia Planitia but marked by curvilinear and polygonal patterns of grooves and troughs; closed polygons as wide as 20 km. Type area: lat 45° N., long 15°. *Interpretation:* Material same as mottled member; patterns may be due to compaction or to tectonic or ground-ice phenomena

Hvr Ridged member—Three small occurrences of mottled plains characterized by concentric pattern of low, narrow ridges about 1 to 2 km wide. Type area: lat 38° N., long 33°; other two outcrops near lat 54° N., Iong 176°. *Interpretation:* Material same as mottled member; origin of ridges unknown but they may be periglacial structures or channel-meander features accentuated by differential erosion

Hvk Knobby member—Similar in appearance to mottled member but generally has higher albedo and abundant small, dark, knoblike hills, some with summit craters. Type area: lat 55° N., long 5°. *Interpretation:* Material same as mottled member; hills may be small volcanoes or remnants of highland terrain or crater rims

Channel-system materials

Deposited in outflow channels and on flood plains; exhibit both depositional and erosional features. *Interpretation:* Channel and flood-plain materials of alluvial origin; some surfaces sculptured by flood waters. Chaotic material formed by disruption of terrain by ground-water release.

Ach, Achp YOUNGER CHANNEL AND FLOOD-PLAIN MATERIALS—Along western margin of map area, form plain as wide as 200 km marked by dark, sinuous, intertwining channels with bars and islands; fill small channels in Arcadia Planitia, along north edge of Tempe Fossae, and in Ophir and Candor Chasmata. Crater counts and superposition relations indicate Amazonian age. Type areas: lat 15° N., long 177° (unit **Ach**) and lat 22° N., long 171° (unit **Achp**)

Hch, Hchp, Hcht OLDER CHANNEL, FLOOD-PLAIN, AND CHAOTIC MATERIALS—Mainly between Valles Marineris and Chryse Planitia, also in other highland locations. Channel deposits longitudinally striated; teardrop-shaped channel bars large and well developed. Flood-plain material occurs adjacent to channels and in lowland plains below channel mouths, smooth and featureless. Chaotic material occurs at source areas and along margins of channels and within some chasmata and craters; generally a mosaic of highland blocks in depressions. Type areas: lat 25° N., long 60° (unit **Hch**); lat 27° N., long 53° (unit **Hchp**); lat 5° S., long 27° (unit **Hcht**)

HIGHLAND TERRAIN MATERIALS

Rock and rock-tectonic units of moderate to high relief; dominate southern and near-equatorial parts of map area. Volcanic mountains and associated lava flows of Tharsis region, although not typical of highland terrain, are included in this physiographic classification because they are superposed on highland terrain or form high plains and locally rugged topographic features.

Western volcanic assemblage

Volcanoes and lava flows in Tharsis region of Mars (Schaber and others, 1978; Scott and others, 1981).

THARSIS MONTES FORMATION—Includes large volcanic shields and associated lava flows of Arsia Mons, Pavonis Mons, and Ascraeus Mons; lava flows similar in morphology to terrestrial basalts (Schaber and others, 1978)

At6 Member 6—Fresh-appearing lava flows form smooth, fan-shaped arrays on flanks of Arsia, Pavonis, and Ascraeus Montes, flows probably originate from fissures along major structural trends. Flanks of these volcanoes exhibit grabens, some concentric. Member also includes most recent fill within central calderas of Tharsis Montes. Type area: lat 5° S., long 117°

At5 Member 5—Widespread around Tharsis Montes volcanoes. Overlies parts of channel and flood-plain deposits (units **Hch**, **Hchp**) of Kasei Valles; contact with upper member (unit **Hsu**) of Syria Planum Formation northwest of Echus Chasma poorly resolved. At places forms elongate, light-colored flow lobes with abundant dark wind streaks. Cut by few faults. Type area: lat 20° S., long 120°

At4 Member 4—Exposed mostly northeast and southwest of member 5. Consists of overlapping light flows with dark wind streaks similar to those of member 5; flows elongate on steep upper slopes, broad on gentler lower slopes. High-resolution images show pressure ridges concentric with lobate flow fronts; minor faulting. Type area: lat 15° S., long 135°

AHt3 Member 3—Makes up central shields of Arsia, Pavonis, and Ascraeus Montes and embays highland terrain west of Arsia Mons and along northwest side of Claritas Fossae, where light and dark flows common. Fewer lobate fronts, pressure ridges, and dark streaks but more faults than in members 4 and 5. Type area: lat 27° S., long 127°

Ht2 Member 2—Occurs in southern and northeastern parts of Tharsis region; embays highland terrain of Tempe Fossae. Composed of relatively smooth flows having broad frontal lobes; fractures and faults common in places. Type area: lat 33° S., long 135°

Ht1 Member 1—Scattered outcrops in southern Tharsis region. Generally forms rough, hummocky surface; mare-type (wrinkle) ridges in places; faults and fractures common locally. Type area: lat 30° S., long 120°

OLYMPUS MONS FORMATION—Includes young lava flows extruded from fissures in plains east of Olympus Mons, young shield lavas of the volcano, and aureole deposits surrounding the volcano. *Interpretation of aureoles:* Formed by gravity spreading of materials forming a larger, earlier Olympus Mons; alternatively, could be ash or lava flows (see text)

Aop Plains member—Embays basal scarp of Olympus Mons and overlaps shield member. Consists of many overlapping smooth lava flows ranging in shape from narrow tongues to broad lobes; flows appear to be extruded from faults and fissures below scarp on southeast side of Olympus Mons. Type area: lat 20° N., long 125°

Aos Shield member—Lava flows form complex, finely textured, interfingering tongues and lobes. Channels and levees extend down flanks of Olympus Mons and across prominent basal scarp on north, east, and south sides, collapse pits common. Type area: lat 15° N., long 135°

Aoa4 Aureole member 4—Uppermost of a series of aureole units around Olympus Mons that formed prior to or contemporaneously with the volcano's basal scarp. Forms broad, semicircular, flat lobes; corrugated, cut by numerous faults that formed scarps and deep troughs and grabens. Type area: lat 25° N., long 145°

Aoa3 Aureole member 3—Forms two lobes; similar to but underlying member 4. Type area: lat 28° N., long 134°

Aoa2 Aureole member 2—Forms three lobes; similar to members 3 and 4; underlies member 3 in relatively small area on southwest side of Olympus Mons; on east side occurs as islands surrounded by plains member. Type area: lat 14° N., long 143°

Aoa1 Aureole member 1—Forms widespread basal aureole; overlaps younger and older fractured materials (units **Hf** and **Nf**). Resembles younger aureole members but smoother and more degraded by wind. Type area: lat 15° N., long 147°

AHcf CERAUNIUS FOSSAE FORMATION—A series of overlapping flows whose surfaces are relatively smooth and even toned to mottled and streaked; trends northeast across older fractured material (unit **Nf**) in Ceraunius Fossae; channels with levees occur in places. Type area: lat 23° N., long 115°. *Interpretation:* Lava flows, most of which originated from fissures

SYRIA PLANUM FORMATION—Volcanic flows of intermediate age that

PLATEAU SEQUENCE—Forms rough, hilly, heavily cratered to relatively flat and smooth terrain covering most of highlands, which are dominant in southern hemisphere. Several units represent transitional stages modified by erosional or depositional processes

Hpl_3 Smooth unit—Forms large areas of flat, relatively featureless plains in southem highlands; locally embays other units of plateau sequence. Faults and flow fronts rare. Type area: lat 43° S., long 105°. *Interpretation:* Thick interbedded lava flows and eolian deposits that bury most of underlying rocks

Npl_2 Subdued cratered unit—Forms plains (mostly in highlands) marked by subdued and partly buried old crater rims. Flow fronts rare. Type area: lat 28° S., long 162°. *Interpretation:* Thin interbedded lava flows and eolian deposits that partly bury underlying rocks

Npl_1 Cratered unit—Most widespread unit in southern highlands; locally extensive in northern plains. Highly cratered, uneven surface of moderate relief; fractures, faults, and small channels common. Type area: lat 45° S., long 148°. *Interpretation:* Materials formed during period of high impact flux; probably a mixture of lava flows, pyroclastic material, and impact breccia

Npld Dissected unit—Similar in occurrence and appearance to cratered unit but more highly dissected by small channels and troughs. Type area: lat 45° S., long 70°. *Interpretation:* Origin same as that of cratered unit but more eroded by fluvial processes

Nple Etched unit—Similar to cratered unit but deeply furrowed by sinuous, intersecting, curved to flat-bottomed grooves that produce an etched or sculptured surface. Type area: lat 45° N., long 55°. *Interpretation:* Cratered unit that has been degraded by wind erosion, decay and collapse of ground ice, and minor fluvial processes

Nplr Ridged unit—Resembles ridged plains material (unit **Hr**) where units adjoin, but ridges generally larger and farther apart, intervening areas rougher and more densely cratered. Type area: lat 15° S., long 163°. *Interpretation:* Most ridges due to normal faulting but others may be volcanic constructs or compressional features

Nplh Hilly unit—Rough, hilly material that resembles in part basement complex (unit **Nb**) and older fractured material (unit **Nf**), but relief is gentler and faulting less intense. Type areas: lat 12° S., long 174° and Nereidum and Charitum Montes surrounding Argyre Planitia. *Interpretation:* Ancient highland volcanic rocks and impact breccia uplifted by tectonism and impact-basin formation during period of heavy bombardment

Hr RIDGED PLAINS MATERIAL—Major occurrences cover an area of about 4,000,000 km^2 extending from Solis Planum to Tempe Fossae. Characterized by broad planar surfaces with flow lobes visible in places and long, parallel, linear to sinuous mare-type (wrinkle) ridges; ridges about 30 to 70 km apart. Type area: Lunae Planum, lat 10° N., long 65°. *Interpretation:* Extensive flows of low-viscosity lava erupted from many sources at high rates, ridges either volcanic constructs or compressional features (see text)

TEMPE TERRA FORMATION—Interpreted to consist of intermediate-age lava flows extruded from small shield volcanoes, fissures, and depressions on Tempe Terra plateau. All members exhibit lobate scarps that may be edges of flows

Htu Upper member—Smooth, light-colored, partly mottled material that embays hilly, mountainous, and fractured terrain of highlands; small (<10-km-diameter) shield volcanoes visible in high-resolution pictures; few faults and fractures; embayed by a lower member (unit $\mathbf{Ht_2}$) of Tharsis Montes Formation and by lower member (unit **Hal**) of Alba Patera Formation. Type area: lat 36° N., long 86°

Htm Middle member—Similar to upper member but faults, fractures, and collapse depressions common. Type area: lat 42° N., long 80°

Htl Lower member—Smooth to rough, uneven surfaces; small faults and collapse depressions common. Overlaps hilly and cratered units (units **Nplh**, $\mathbf{Npl_1}$) of plateau sequence but is embayed by upper and middle members of Tempe Terra Formation. Type area: lat 39° N., long 84°

HIGHLY DEFORMED TERRAIN MATERIALS—The origin and composition of these rock units are only surmised because multiple sets of fractures and grabens have obscured original characteristics. The units are interpreted to consist of impact breccia interlayered with volcanic flows and to intergrade locally

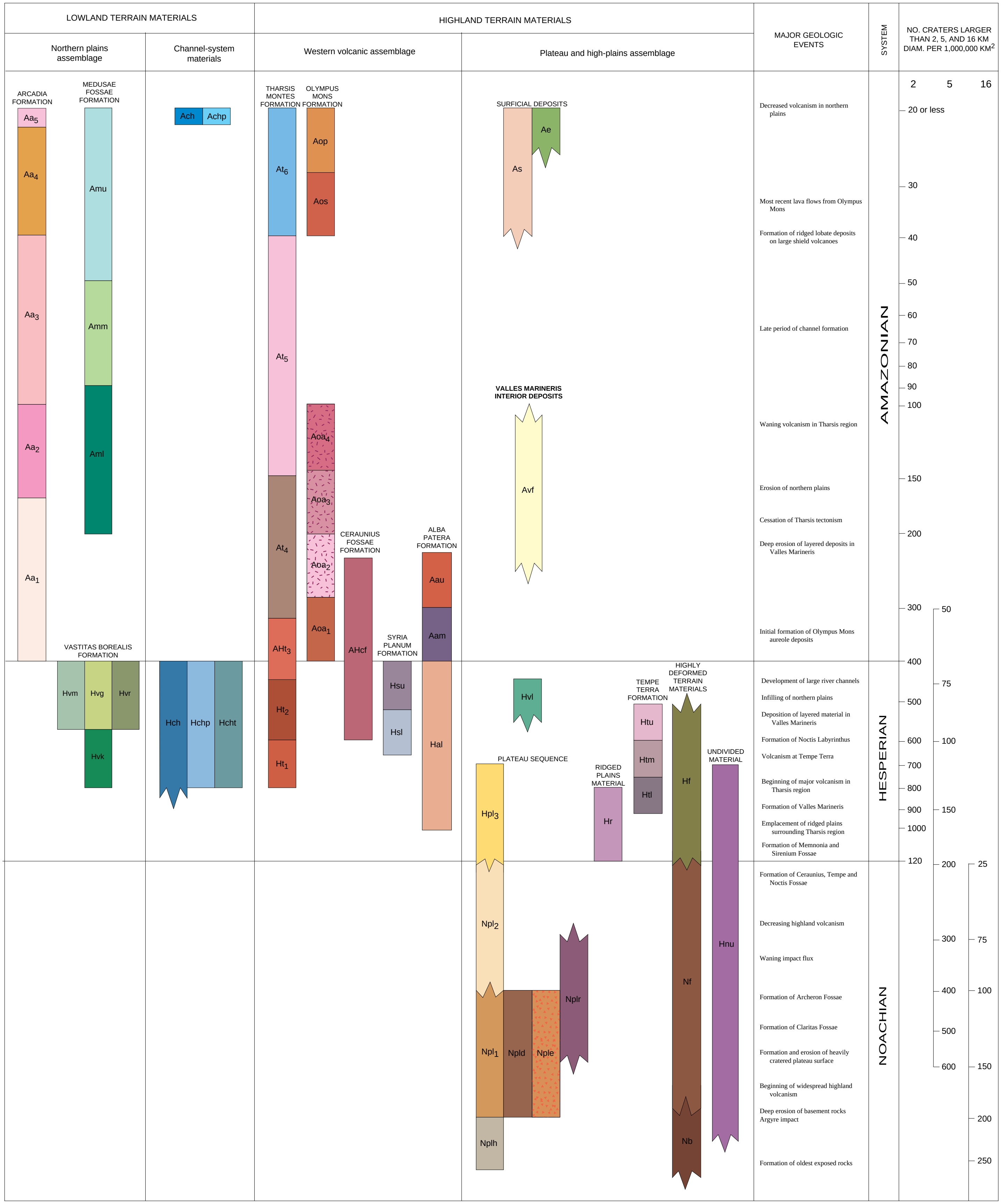
Hf Younger fractured material—Occurs mostly around Valles Marineris and Syria and Sinai Plana and northwest of Pavonis Mons. Forms relatively smooth, raised surfaces of moderate relief with fractures, grabens, and collapse depressions. Overlies other highly deformed terrain materials but is embayed and partly covered by Syria Planum Formation and other younger rock units. Type area: lat 5° S., long 103°

Nf Older fractured material— similar to fractured material but widespread, has greater relief, is more highly deformed, and faults are more complexly oriented; impact-crater outlines largely destroyed. Type area: lat 20° S., long 109°

Nb Basement complex—Undifferentiated material characterized by highly complicated structure and prominent relief. Most common in Claritas and Mareotis Fossae areas. Type area: lat 28° S., long 100°

HNu UNDIVIDED MATERIAL—Forms hills and small knobs adjacent to highland-lowland boundary scarp that extend almost to north map border. Also forms walls and interior mountains in Valles Marineris and associated canyons and channels, as well as hummocky terrain and scarps along edges of Chryse and Acidalia Planitiae. No specific type area. *Interpretation:* Erosional remnants and exposures of plateau sequence, highly deformed terrain materials, ancient crater rims, and some other materials that are older than surrounding rock units

CORRELATION OF MAP UNITS, GEOLOGIC EVENTS, AND CRATER DENSITIES IN THE WESTERN EQUATORIAL REGIONS OF MARS

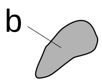


CONTACT—Dashed where approximately located or gradational, or where arbitrarily located based on crater densities of bounded map units

FAULT OR GRABEN—Bar and ball on downthrown side of fault

MARE-TYPE (WRINKLE) RIDGE—Symbol on ridge crest

NARROW SINUOUS CHANNEL—Wide age range



TEARDROP-SHAPED BAR OR ISLAND ON CHANNEL FLOOR—May be erosional or depositional feature

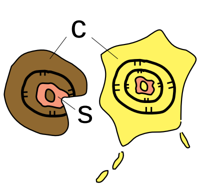
DEPRESSION

CALDERA

JOINT OR FRACTURE PATTERN

HIGHLAND-LOWLAND BOUNDARY SCARP—Diffuse zone of transition between highland and lowland physiographic provinces; not shown where buried

CREST OF BASAL SCARP OF OLYMPUS MONS—Dashed where buried



IMPACT CRATER MATERIALS—Symbol "c" denotes crater-rim and ejecta material; yellow if superposed, brown if partly buried. May include rim crest (hachured), central ring (inner circular feature, also hachured), and central peak. May also include secondary craters outside crater aprons. Symbol "s" and orange color denote smooth floor; floor material of diverse origins, may be eolian or volcanic fill. Not mapped are material of superposed craters less than about 100 km across, rims of partly buried craters less than about 150 km across, and smooth crater floors less than about 30 km across

MOUNTAIN—Relative age and origin unknown

VOLCANO—Relative age unknown. May have central caldera and radial channels

INTRODUCTION

This map of the western equatorial region of Mars supersedes previous geologic maps based on Mariner 9 data. It represents a more advanced study of the geology afforded by the higher resolution, better quality, and nearly complete coverage of the Viking Orbiter images. The map is the first of three in a series planned to cover the entire planet, portraying its lithology, stratigraphy, and structure. The text describes the major tectonic, volcanic, and fluvial episodes that have contributed to Mars' evolutionary history. The base used for compilation reflects improved imagery and photogrammetry and updated nomenclature.

Geologic units were identified and mapped from 1:2,000,000-scale photomosaics and individual images, most of which range in resolution from 130 to 300 m/pixel. The units were assigned on the correlation chart to the three time-stratigraphic systems previously formulated (Scott and Carr, 1978) from the Mariner 9 mapping. Relative ages of the units were established by stratigraphic and structural relations and by crater size-frequency distributions.

Cumulative crater densities of units in the three systems are also shown on the correlation chart. Because of crater degradation, resurfacing, and declining crater-flux rates, relative ages of increasingly older surfaces on Mars are determined by densities of progressively larger craters. Thus density scales for craters larger than 2, 5, and 16 km in diameter were selected for relative-age correlation within the Amazonian, Hesperian, and Noachian Systems, respectively. Overlap of the scales was empirically determined by calculating ratios of crater densities at different diameters for units most likely to preserve a wide range of crater sizes.

The Viking map series shares some of the uncertainties inherent in earlier maps of Mars in that many of the primary depositional characteristics of units have been modified and obscured by erosion, deposition, and tectonism. In particular, deformation has destroyed all morphologic properties of the materials that are normally used to infer rock type in the highly faulted and fractured areas north and south of Tharsis Montes and on the Tempe Terra plateau. Three units from these areas are grouped under highly deformed terrain materials and mapped as basement complex (unit **Nb**) and fractured materials (units **Hf**, **Nf**) of different ages, but they are considered to be locally gradational.

The map units are broadly subdivided into lowland and highland terrain materials. The lowland terrain consists of extensive plains north of the highland-lowland boundary scarp that lies mostly in the northern hemisphere. Much of the lowland region is covered by small knobs and conical hills. South of the boundary scarp, plateau terrain of higher elevation and greater relief extends to the south polar region.

A rock-stratigraphic classification of both formations and members is employed here for the first time in the geologic mapping of Mars. Its use minimizes the need for adjectival map-unit descriptions that may be both inadequate and confusing. In the lowland plains as well as in the highlands, many units appear to be transitional. Some contacts are mapped largely on the basis of crater-density discontinuities; these "statistical boundaries" are dashed. To avoid obscuring relations among geologic units, only superposed crater blankets wider than 100 km and partly buried impact craters larger than about 150 km in rim-crest diameter are mapped. No attempt has been made to classify craters by relative age according to their degree of degradation, but the more significant factor—the stratigraphic position of craters relative to adjacent terrain—is shown by color. This relative position is determined by embayment, overlap, and transection relations.

This Viking map thus differs from earlier Mariner 9 maps in many respects, of which the following are most significant: (1)a nearly three-fold increase of mapped rock units over those on the geologic map of Mars based on Mariner images (Scott and Carr, 1978); (2) the subdivision of lava flows associated with major eruptive episodes at Tharsis Montes and other large volcanic centers; (3) the expansion of areas mapped as channel-system deposits, especially their greater extension into the northern plains; (4) the recognition of smooth, soft-appearing, easily eroded planar deposits of possible ash-flow or eolian origin that cover large areas in the equatorial region of Medusae Fossae; and (5) the addition of many small- to moderate-size features interpreted as volcanoes and source vents in the southern highlands and on the Tempe Terra plateau. Also, several units have been assigned to different time-stratigraphic systems. For example, the mottled plains material, formerly classified as Noachian in age, has been placed in the upper part of the Hesperian System on the basis of crater counts and stratigraphic position, and it is now considered to form part of the Vastitas Borealis Formation.

Detailed studies of the stratigraphy and geology of Mars have increased dramatically since the Mariner 9 orbiter first transmitted an encyclopedic pictorial library of the surface. Higher resolution data gathered from the Viking mission have enabled surface processes to be described in greater detail and their interpretations modified or changed. Much of this

Noachian System

The Noachian System consists of the oldest rocks on Mars and includes most of the units mapped in the southern highlands. The rocks are generally densely cratered and, in places, highly deformed by faulting. Although the Martian highlands have roughly twice the crater density of the lunar Nectarian terrain, the shape of the distribution curve of craters larger than 20 km in diameter in rock units formed during Noachian time is similar to that of the Nectarian (Tanaka, 1984)—the second oldest period of the Moon (Wilhelms and others, 1978). The Nectarian, therefore, may be similar in age to the middle of the much longer Noachian. Because the Martian highlands are dominantly of middle Noachian age, they may be younger, on the average, than the lunar highlands, which have substantial proportions of both Nectarian and pre-Nectarian materials. The fact that fewer large impact basins have been found on Mars than on the Moon may be explained by differences either in the flux of large impacts between the two bodies or in the average age of their highlands. Models for overall size-frequency distributions of craters larger than 10 km in diameter on Martian highland surfaces suggest either that the early population of crater-producing bodies followed a log-normal distribution law (Woronow, 1977; Gurnis, 1981), or that many craters in the 10- to 30- km size range were obliterated (Chapman and Jones, 1977).

The *basement complex* (unit **Nb**) is the oldest identifiable material in the western hemisphere of Mars (Scott and King, 1984). The unit is highly faulted and cratered and has prominent relief. Most exposures occur in three areas. (1) In Claritas Fossae (lat 28° S., long 100°), the basement complex is transitional with other highly faulted material (unit **Nf**) that forms a raised block-faulted corridor extending northwest toward the Tharsis Montes. (2) On the north edge of the highland Tempe Terra plateau, an outcrop that forms a degraded ridge (centered at about lat 45° N., long 84°) along the northwest margin of the plateau appears to have been uplifted and tilted by high-angle faulting. (3) In the highlands around the Tharsis-Syria swell, relatively small isolated peaks project well above the surrounding plains that are flooded and partly buried by lava flows. The basement complex may also be exposed in the lower walls of Valles Marineris and in some of the mountains ringing Argyre Planitia. The relatively high relief associated with basement remnants may be due partly to erosion of a formerly high regional surface, but it is also the result of structural uplift along normal faults produced by early tectonism and possibly by impacts. The basement complex and *older fractured material* (unit **Nf**) predate major tectonic episodes and are possibly older than the beginning of the Tharsis-Syria swell (Scott and Tanaka, 1980; Plescia and Saunders, 1982). These units probably consist mostly of impact breccia formed during early stages of high meteorite flux, similar to the breccias of the lunar highlands.

The southern highlands consist largely of the seven rock units of the plateau sequence. The highlands nearly encircle the Tharsis-Syria swell, extending from Terra Sirenum in the southwest to Aonia and Noachis Terrae in the south to Meridiani, Xanthe, and Tempe Terrae in the east and north. Their continuity is interrupted by channels east of Valles Marineris and by Kasei Valles. Some units in the sequence have clearly distinguishing morphologic characteristics, whereas others represent transitional stages in resurfacing of the highlands by lava flows and eolian and fluvial processes.

The *hilly unit* (unit **Nplh**) at the base of the plateau sequence forms a rough terrain of irregular peaks, ridges, and ancient crater rims separated by relatively flat areas. It is not as intensely faulted as the basement complex, but the two units are difficult to distinguish in small isolated outcrops. Typical exposures of the hilly unit occur around Argyre Planitia and along the southwest edge of Daedalia Planum. The prominent relief of the unit appears to be due in places to normal faulting, as indicated by the linearity of steep ridges and hills. In some areas the hilly unit contains small- to moderate-size features interpreted to be volcanoes. Around Argyre Planitia, the floor of an impact basin, the unit forms features that range in size from small rounded hills to large massifs. Here the unit closely resembles the Alpes and Montes Rook Formations encircling the Imbrium and Orientale Basins on the moon (Wilhelms and McCauley, 1971; Hodges, 1980), and it is interpreted to have a similar origin. The smaller hills are probably ejecta; the larger blocks appear to be uplifted and tilted crustal rocks.

The most extensive unit in the Noachian System is the *cratered unit* (unit **Npl$_1$**), distinguished by a high density of craters in all sizes, particularly those larger than 10 km in diameter. Craters are both partly buried and superposed, and intercrater areas are rough but without the prominent relief of the hilly unit. The occurrence of lava-flow fronts and a profusion of impact craters throughout the unit suggest that it consists of volcanic material interbedded with impact breccia. Where these materials have been highly dissected by small channels, they are mapped as the *dissected unit* (unit **Npld**). The small channels have patterns resembling those of terrestrial streams and may be due to runoff from ground-water seepage (Pieri, 1980, p. 148) or rainfall (Masursky and others, 1977). Some of the larger and more pronounced channels are mapped individually. Where the cratered materials are etched into irregular grooves and hollows, they are mapped as the *etched unit* (unit **Nple**), which exhibits features similar to those on Earth that are sculptured by wind, such as yardangs, deflation pits, and depressions (McCauley, 1973).

The *ridged unit* (unit **Nplr**) also occurs throughout the highlands. It is traversed by rough, prominent, sublinear to irregular ridges, which differ in size and form both from large ridges in the older hilly unit and from wrinkle ridges in the younger ridged plains material (unit **Hr**). Generally the Noachian ridges are less ordered in continuity and spacing and have more relief than the Hesperian ridges, but they follow the same regional trends, forming a great arc around the south end of the Tharsis swell. In places the ridges have steep flanks that may be fault scarps.

Many areas within the highlands have been smoothed and subdued by a mantling material that is interpreted to be of volcanic and eolian origin. Crater rims, ridges, and hills are recognizable beneath the mantle, but smaller irregularities, which elsewhere contribute to the coarse texture of intercrater areas, are buried. The mantle and underlying material are mapped together as the *subdued cratered unit* (unit **Npl$_2$**) of the plateau sequence. Other highland areas are more thickly covered by younger materials that form the smoother, relatively flatter surfaces of the *smooth unit* (unit **Hpl$_3$**); its Hesperian age is indicated by crater counts.

Rock units within the highlands and lowlands that cannot be either recognized on the basis of morphologic characteristics or placed precisely in a stratigraphic position within the Hesperian or Noachian Systems are grouped as *undivided material* (unit **HNu**). This unit is mapped in the walls of Valles Marineris and in chasmata and deep channels. It also forms clusters of knobby and round hills north of the highland-lowland boundary scarp. (Southward from this scarp, these hills are progressively larger and less degraded and can be identified as remnants of units of the plateau sequence.)

Hesperian System

The Hesperian System records extensive evidence of volcanism, tectonism, and canyon and channel formation that is relatively unscathed by impact craters and other severe degradation. Crater size-frequency distributions for pristine Hesperian surfaces closely follow a –2 power law for craters larger than about 2 km in diameter (Neukum and Wise, 1976). This relation allows comparison of crater ages determined for different diameter ranges. Densities of either 2- or 5-km craters were determined for most Hesperian surfaces and are used to designate relative ages on the correlation chart, although some surfaces have been degraded to the extent that densities of craters larger than 5 km in diameter more accurately represent the crater age of the surface. Hesperian materials cover highland terrain in thick expansive sheets and also as patches of intercrater plains; they partly cover the northern plains and floors of chasmata. They form extensive volcanic flows in the Tharsis Montes, Alba Patera, Syria Planum, and Tempe Terra regions. Most Amazonian plains materials are surrounded by or contain windows of Hesperian materials. We estimate that more than half of the map area was resurfaced during the Hesperian Period.

Younger fractured material (unit **Hf**) is exposed in Claritas, Thaumasia, and Ulysses Fossae and in areas adjacent to Valles Marineris, Syria Planum, and Uranius Patera. Although the unit intergrades locally with the older fractured material (unit **Nf**), it is cut by fewer faults of less complexity. The Hesperian fractured unit may have been partly resurfaced by lava flows during later stages of less intense tectonic activity.

The most extensive unit in the Hesperian System, the *ridged plains material* (unit **Hr**), is characterized by smooth surfaces with widely spaced, long, sinuous wrinkle ridges similar to those of the lunar maria. The unit is interpreted to consist of lava flows (Scott and Carr, 1978, Greeley and Spudis, 1981). It is the basal rock-stratigraphic unit of the Hesperian

System on both the Mariner 9 map of Mars (Scott and Carr, 1978) and the present map. Ridged plains material occurs in some lowland areas and is widespread throughout the highlands, particularly from Lunae Planum to Solis Planum, where its western margin is buried by the lower member (unit **Hsl**) of the Syria Planum Formation. It is also exposed in scattered patches around the south end of the Tharsis swell, forming a broad arc that extends into Amazonis Planitia. Northwest of Kasei Valles, a major disconformity is clearly marked by the overlap and truncation of faults and fractures in the ridged plains unit by younger flows from the Tharsis volcanoes. This boundary, more than 400 km long, is nearly linear and may be fault controlled.

Most of the *Tempe Terra Formation* consists of smooth, nearly featureless material. Low-relief, overlapping lobate scarps that may be lava-flow edges are visible in all members. The formation occurs within the fractured uplands of Tempe Terra, including Tempe and Mareotis Fossae. Its three members (units **Htl**, **Htm**, and **Htu**) probably consist of lava flows erupted from small shield volcanoes, fissures, and circular to elongate collapse depressions that are common throughout the outcrop area. The lava flows blanket and embay cratered plains and highly fractured terrain of Noachian age; they are in turn embayed by younger flows.

Within the Valles Marineris and adjacent chasmata are mesas and rounded hills that consist of alternating light and dark horizontal beds of the *layered material* (unit **Hvl**) *of the Valles Marineris interior deposits*. The tops of these eroded remnants in places approach the level of the surrounding plateau, suggesting that the layered materials once filled the canyons. The origin of the unit is uncertain. According to one hypothesis (McCauley, 1978), the layered materials accumulated as waterlaid sediments in large lakes within the canyons; their deposition was followed by episodes of catastrophic draining throughout the canyon systems. The lake sediments may consist of materials eroded from canyon walls, eolian material, and volcanic ash from the Tharsis volcanoes. Alternatively, Peterson (1981) has ascribed the occurrence of layered deposits in Hebes Chasma (just north of the main Marineris system) to pyroclastic infilling of the chasma from sources beneath its floor.

In the western volcanic assemblage, crater densities indicate about the same age for the *lower members* (units **Hal**, **Ht$_1$**, and **Ht$_2$**) *of the Alba Patera and Tharsis Montes Formations* and the *lower and upper members* (units **Hsl** and **Hsu**) *of the Syria Planum Formation*. They are clearly identified as lava flows by their morphology, as are the upper members of these formations. The lowermost member of the Alba Patera Formation nearly encircles the volcano and extends as far as 1,500 km from its center; it embays the older fractured material (unit **Nf**) around the east edge of Acheron Fossae. Elsewhere the outer boundary of the lowermost member is not clearly defined except where the member is overlapped by the plains member (unit **Aop**) of the Olympus Mons Formation (lat 23° N., long 123°). Many of the lower, Hesperian-age flows of the Tharsis Montes Formation probably originated from fissures on the lower slopes of Arsia Mons and from around the base of Uranius Patera. They occur as far as 2,000 km from the Tharsis Montes and have more subdued relief and generally lower elevations than the younger members of the formation. The lower member of the Syria Planum Formation appears to have been extruded from fissures, whereas the upper member probably issued from fissures and also from partly buried calderas near the crest of Syria Planum.

The *older channel, flood-plain, and chaotic materials* (units **Hch**, **Hchp**, and **Hcht**) are widespread, mostly northeast of the Valles Marineris. Martian outflow channels are commonly sinuous, braided, many kilometers wide, and more than a thousand kilometers long. Most originate from chasmata and chaotic material (unit **Hcht**), although the Mangala Valles, in the western part of the map area, appear to head at a fissure. Channel floors are marked by striations, terraces, and teardrop-shaped bars or islands (map symbol "**b**"). Outflow channels that debouch onto the floor of Chryse Planitia are mostly obscured by flood-plain material and younger lava flows of the lowermost member (unit **Aa$_1$**) of the Arcadia Formation. Crescentic depressions that in size and shape closely resemble meander patterns of terrestrial rivers are recognized within the channel banks of Ares Vallis. These depressions in isolated exposures of flood-plain material occur in Acidalia Planitia as far north as lat 45° N., suggesting that flooding from the outflow channels was extensive (Scott,1982). The channel and adjacent flood-plain materials are overlapped by members (units **At4** and **At5**) of the Tharsis Montes Formation in the Kasei Valles, and by the floor member (unit **Avf**) of the Valles Marineris interior deposits in Echus Chasma. Most of the channels cut ridged plains material (unit **Hr**) in Lunae Planum and Chryse Planitia and some cut the layered member (unit **Hvl**) of the Valles Marineris interior deposits within Gangis Chasma; thus the channels are largely middle to upper Hesperian in age. Crater densities of scoured channel and flood-plain materials south of Chryse Planitia generally confirm this age designation (Carr and Clow, 1981); an exception may be channel material in Mawrth Vallis (lat 22° N., long 12° to 20°), for which crater counts (Masursky and others, 1980) suggest a late Noachian to early Hesperian age.

The formation of the channels has been attributed to erosion by running water by most authors, for example, Baker and Milton (1974) and the Mars Channel Working Group (1983); other suggested processes include wind erosion (Cutts, 1973), lava erosion (Carr, 1974), and glaciation (Lucchitta and others, 1981). However, sufficient water may not have been available to erode the deeper channels of Kasei, Ares, and Shalbatana Valles (Sharp and Malin, 1975). These workers suggested that the deeper channels originated by tectonic subsidence and by sublimation of ground ice, which produced incipient linear depressions that rivers later eroded into channels. Various processes have been proposed to account for the release of water. Masursky and others (1977) suggested that large volumes of water may have come from the melting of interstitial ice in the subsurface because of volcanic heating. Soderblom and Wenner (1978) proposed that scarps or small channels retreating headward occasionally intercepted subsurface fluid reservoirs, causing sudden increases in flow rates. Carr (1979) postulated that artesian conditions developed beneath large craters in the low region south of Chryse Planitia, allowing the rapid release of huge volumes of water.

The *Vastitas Borealis Formation* contains the oldest rocks in the northern plains assemblage. Its four members are distinguished on the basis of secondary morphologic characteristics and are degraded to varied degrees; craters smaller than 5 km in diameter have been largely obliterated. Densities of larger craters indicate that the lowermost member is middle Hesperian in age and that the other members are late Hesperian. The members intergrade with and do not appear to overlap one another. Large areas of the formation have many conical hills whose crests are darker than their flanks; some hills have summit craters and may be volcanoes. Where the hills are closely spaced or coalesce into clusters, they are mapped as the *knobby member* (unit **Hvk**). The *ridged member* (**Hvr**) is characterized by ridges that commonly form whorled patterns resembling fingerprints. The *grooved member* (unit **Hvg** young rock units have been further subdivided and, where practicable, assigned formation names.

The plains-forming *Arcadia Formation* comprises five members (units **Aa$_1$** to **Aa$_5$)** whose age range defines and spans the Amazonian Period (Scott and Carr, 1978). All of the members are exposed within Arcadia Planitia, and are separated from the more rugged, plateau-forming highlands to the south by the highland-lowland boundary scarp. On Mariner 9 maps (Morris and Dwornik, 1978; Morris and Howard, 1981), the formation was interpreted to consist of thick sequences of lava flows, a conclusion supported by the present mapping. The common boundaries of the older members are poorly defined and, in places, they are mapped arbitrarily on the basis of variations in crater density or slight differences in texture and albedo of the bounded units. Landforms that are commonly visible on high-resolution images appear to be lobate flow fronts, pressure ridges, small volcanoes, and collapsed lava tubes or lava channels.

The *Medusae Fossae Formation* occurs mostly north of the highland-lowland boundary scarp between the highlands south of Medusae Fossae and the lowlands of Amazonis Planitia. It consists of three members (units **Aml**, **Amm**, and **Amu**) deposited in horizontal sheets; no bedding is visible on high-resolution Viking images. Total thickness of the members may exceed 3 km, according to the most recent topographic maps of the region (S.S.C. Wu and Raymond Jordan, U.S. Geological Survey, unpub. data, 1985). The surfaces of the members are relatively smooth and flat to gently rolling; they have been etched and serrated by wind, particularly along their edges (Ward, 1979). The deposits are less hilly and cratered than those of the highlands, but have more relief and are lighter colored than lava flows of the Arcadia Formation. The Medusae Fossae Formation has been provisionally interpreted to consist of ash flows (Malin, 1979). Its surfaces resemble both welded and nonwelded ash-flow tuffs in the Basin and Range province of the Western United States (Scott and Tanaka, 1982). Elongated depressions in the upper member may represent some partly buried sources of the ash. The lower member contains dark resistant material that may be lava flows.

The western volcanic assemblage consists of relatively young materials erupted from and around large volcanoes and fissure vents. The Amazonian-age units of the assemblage consist of the *upper three members of the Tharsis Montes Formation*, all of the *Olympus Mons Formation*, and the *upper two members of the Alba Patera Formation. Member 3* (unit **AHt$_3$**) of the *Tharsis Montes* and the entire *Ceraunius Fossae Formation* straddle the Amazonian-Hesperian boundary. (The Syria Planum Formation, also included in the assemblage, is entirely of Hesperian age and has been described above.)

The Tharsis Montes Formation and its giant source volcanoes (Arsia, Pavonis, and Ascraeus Montes) constitute the best known and one of the largest sequences of lava flows on Mars. The flows are thinly spread across the broad, gently arched Tharsis swell, indicating that they had low viscosities and yield strengths, high eruption rates, and a basaltic composition (Moore and others, 1978). Relative ages of the members were determined mainly by stratigraphic relations and in places by differences in degradation of the flows. Crater counts on the various members verify age relations and help to establish correlations between flows in some widely separated areas. Crater counts also indicate that eruption of lava flows of the Tharsis Montes Formation appears to have been nearly continuous. The older Hesperian members retain some morphologic features characteristic of the younger members (units **At$_4$**, **At$_5$**, and **At$_6$**), including tongue-shaped flows with lobate fronts. These observations, together with low crater densities and the relative absence of faults and fractures transecting the flows, indicate that the style of Tharsis volcanism remained unchanged as tectonism declined late in Martian history.

The Olympus Mons Formation consists of six members. The oldest four (units **Aoa$_1$** to **Aoa$_4$**) are aureole deposits of uncertain composition and origin. They are broad, flat, sheetlike, lobate deposits whose surfaces are grooved, ridged, and faulted. Formation of the aureoles is considered by most workers to have been caused by either volcanic or gravity-assisted mechanisms. Proposed volcanic origins include lava flows (McCauley and others, 1972), moberg ridges (Hodges and Moore, 1979), and welded and nonwelded ash-flow tuffs (Morris, 1982). Postulated gravity-assisted processes include low-angle thrusting of layered material from beneath the Olympus Mons shield (Harris, 1977), gravity sliding of shield flanks (Lopes and others,1980), and gravity spreading of shield flanks (Francis and Wadge, 1983)—perhaps with the aid of ground ice (Tanaka, 1985). The ages of the aureoles relative to those of most other units in the Tharsis region can be only broadly determined. The aureoles are overlapped by the postscarp shield member (unit **Aos**) of the Olympus Mons Formation that was extruded from the summit and flanks of the volcano. This member and the aureoles are, in turn, buried in places by flows of the plains member (unit **Aop**) that originated from fissures east of the shield. The lowermost aureole member underlies member 4 of the Tharsis Montes Formation and member 3 of the Arcadia Formation but overlaps fractured materials of Hesperian and Noachian age. A few older flows from Olympus Mons are sharply truncated at the scarp or are degraded and exposed in windows above the scarp. Where these older surfaces exhibit faults and grabens, they have been mapped as younger fractured material (unit **Hf**). Although crater counts of the aureole deposits have been attempted (Hiller and others, 1982), their accuracy is questionable because mass wasting of the rough and apparently soft surfaces of the aureoles promotes rapid deterioration of crater forms. The density of positively identifiable impact craters on the aureoles is lower than that of younger materials that embay the aureoles (Morris, 1982). The position of the aureole deposits in the stratigraphic column is thus provisional.

Lava flows of the Ceraunius Fossae Formation (unit **AHcf**) originate from complex fracture systems that extend northeastsouthwest across a broad saddle between Ascraeus Mons and Alba Patera. The flows bury most of the fault fissures from which they were extruded and partly cover the lower member of the Alba Patera Formation. They are overlapped by the plains member of the Olympus Mons Formation and by younger members of the Tharsis Montes Formation.

The Alba Patera Formation ranges in age from Hesperian to early Amazonian and contains three members. The upper member (unit **Aau**) covers a depressed circular area as much as 600 km in diameter at the center of the volcanic deposits. It partly buries nested calderas at the crest of the volcano and covers radial and concentric faults of Alba and Tantalus Fossae that transect the middle (**Aam**) and lower (**Hal**) members of the formation.

Younger channel material (unit **Ach**) and *flood-plain material* (unit **Achp**) occur (1) in a broad outflow channel that debouches into the western part of Amazonis Planitia; (2) as small channel deposits in Arcadia Planitia on the lowermost member (unit **Aa$_1$**) of the Arcadia Formation; (3) as minor flood-plain deposits that were transported down graben valleys along the north edge of Tempe Fossae; and (4) associated with debris flows in Candor Chaos.

Surficial materials of various origins occur locally throughout the map area. *Slide material* (unit **As**) is common in Valles Marineris (Lucchitta, 1978, 1979) and along the northwestern part of the basal scarp of Olympus Mons. Origin of the huge spatulate, concentrically ribbed deposits on the northwest flanks of the Tharsis volcanoes is uncertain. The surfaces of these deposits are hummocky: they exhibit many small hills and closed depressions whose size decreases away from the deposits' source. All of these features are characteristic of large volcanic-debris avalanches noted in many volcanic regions on Earth (Siebert, 1984). The concentric ridges also resemble recessional moraines in Iceland and could have been emplaced on former local ice caps (Lucchitta, 1981). *Eolian deposits* (unit **Ae**) tend to concentrate in low areas where they mantle underlying terrain; yardangs and dunes are visible in some high-resolution pictures. Large patches of the unit cover parts of the aureoles around Olympus Mons. Other eolian materials appear as bright or dark streaks in the lee of obstacles such as craters and hills, although some of the dark streaks may be areas swept free of loose debris (Thomas and Veverka, 1979). The *floor material* (unit **Avf**) *of the Valles Marineris interior deposits* probably consists of a combination of volcanic, eolian, fluvial, and landslide fill derived in part from erosion of the layered material (unit **Hvl**).

Unassigned materials

Isolated mountains, hills, and domes occur throughout the highlands, but as a group they are not assigned a position in the stratigraphic column. They may have been formed relatively early in Martian history, as they are commonly embayed by younger materials, but their small size does not permit reliable crater counts. Those having features interpreted to be volcanic, such as summit depressions and flow patterns on their flanks and around their bases, are shown in red and are designated by the symbol "**v**". Others may be remnants of the basement complex or of the hilly unit of the plateau sequence; these are shown in dark gray and are designated by the symbol "**m**".

Mantling deposits of volcanic, eolian, and alluvial origin form the smooth plains that cover the floors of many craters. These deposits are generally more common and thicker in older craters than in younger ones. Because their crater densities indicate a wide age range, they are not shown on the correlation chart; they may be mostly Amazonian in age. The mantling deposits are shown in orange and designated by the symbol "**s**".

STRUCTURAL HISTORY

The tectonic history of the western equatorial region is reconstructed from transection relations among various tectonic features and the stratigraphic units. Intermediate- and late-stage tectonism in the map area is mostly related to or associated with the Tharsis swell. Older regional structural patterns in the map area may be related to early Tharsis tectonism, but this relation has yet to be established. Such structural patterns include: (1) fault sets in Claritas, Thaumasia, Coracis, Melas, and Nectaris Fossae that predate radial Tharsis faulting; (2) a broad, Tharsis-centered arc formed by old volcanoes in Terra Sirenum (Scott and Tanaka, 1981); (3) the semicircular Acheron Fossae arch containing concentric faults and volcanic structures; and (4) possible ancient fractures associated with initial structural development of Valles Marineris (Masson, 1977).

Radar profiles (Downs and others, 1982) indicate that the northeast-trending, elliptically shaped Tharsis swell may be as much as 7 km higher than the surrounding terrain Theories of its formation are speculative, proposed models include isostatic uplift followed by flexural loading (Phillips and others, 1973, Banerdt and others, 1982), thick accumulations of volcanic flows extruded through a locally thin lithosphere (Solomon and Head, 1982), and crustal thickening by intrusion (Willemann and Turcotte, 1982). Our mapping suggests that development of the Tharsis swell involved a complex history of episodic tectonism and volcanism on local and regional scales. The most intense deformation around Tharsis occurred during the Noachian and Hesperian Periods, resulting in fault systems that trend mostly northeast to north but also radial to a sequence of centers that shifted from Syria Planum to Pavonis Mons (Wise and others, 1979; Plescia and Saunders, 1982). These faults are visible in the highly deformed older fractured material and basement complex (units **Nf** and **Nb**) of Thaumasia, Claritas, Ceraunius, Acheron, Mareotis, and Tempe Fossae, in the younger fractured material (unit **Hf**); and in the lava flows of the Alba Patera, Syria Planum, and Tempe Terra Formations. The radial fractures deviate around local circular structures that include Alba Patera, Syria Planum, and features on the Tempe Terra plateau.

As the intensity of Tharsis faulting diminished, wrinkle ridges similar in morphology to lunar mare ridges formed on smooth plains surfaces of Hesperian age; prominent occurrences include Solis, Felis, Sacra, and Xanthe Dorsa. The ridges trend concentrically to the Tharsis swell within a wide belt extending several thousand kilometers from its center. Most ridges predate the formation of Kasei and Maja Valles and postdate intense faulting in the Thaumasia and Tempe Fossae regions. They may be either nearly parallel or normal to faults and linear depressions; some grade into large, linear edifices interpreted to be volcanoes, as at lat 46° S., long 172°. Proposed origins of ridges include: eruption of volcanic material along structurally controlled linear trends (Greeley and others, 1977), compressional folding associated with the Tharsis swell (Wise and others, 1979; Watters and Maxwell, 1983), and compressional folding caused by contraction of the planet's surface (Gifford, 1981, p. 322).

Most development of the Valles Marineris canyon system and associated outflow channels and chaotic terrain occurred during the Hesperian Period. The canyons are incised in a thick stack of plateau sequence rocks, capped around their western part by ridged plains material and the Syria Planum Formation. Significant canyon-scarp retreat appears to have followed emplacement of these cap rocks, but it is not known if all of these units were breached by the developing canyon system. Possibly the ridged plains material of Lunae and Solis Plana was in part lava flows extruded from fault fissures that later formed Valles Marineris. Compared with Noctis Labyrinthus, the large canyons of Valles Marineris are more highly developed and probably older, possibly early Hesperian. Proposed processes of canyon formation include ice sublimation (McCauley and others, 1972), crustal rifting (Sharp, 1973; Frey, 1979), and extrusion or relocation of huge volumes of underlying magma (Sharp, 1973; Schonfeld, 1979). Eolian and fluvial excavation of the central Valles Marineris canyons was minor at most (Sharp and Malin, 1975). The following sequence of formation of the canyons and associated channels is suggested by the additional geologic information obtained by our mapping. (1) Deep-seated heating resulted in crustal expansion and rifting analogous to the East African rift system on Earth, but the thick and homogeneous Martian crust was cut by rifts that are broader and straighter than those on Earth (Frey, 1979). Rift valleys attained about half their present size from adjustment to regional uplift. (2) Possible concurrent volcanism from rift faults formed the ridged lavas in Lunae, Solis, and Sinai Plana. Withdrawal of lava caused further canyon subsidence. (3) Layered deposits were emplaced either in lakes that filled the canyons (McCauley, 1978) or as ash-fall deposits (Peterson, 1981). (4) Outflow channels formed from catastrophic release of water from some chasma lakes (McCauley, 1978) or aquifers (Soderblom and Wenner, 1978; Carr and Clow, 1981). (5) Canyons continued to expand by faulting and landsliding. Eolian and fluvial erosion removed and transported most layered deposits.

Infilling of the northern plains apparently commenced with emplacement of the ridged plains material (unit **Hr**), although evidence of possible earlier deposits may have been destroyed by extensive erosion along the highland-lowland boundary. Scarp retreat along this boundary is evidenced by knobby remnants (unit **HNu**) of the highland plateau sequence that occur several hundred kilometers north of the boundary's present position. Ridged plains material is overlain in Chryse Planitia by channel (unit **Hch**) and flood-plain (unit **Hchp**) deposits and the lowermost member (unit **Aa1**) of the Arcadia Formation. Several explanations for the early formation of the northern lowlands have been postulated, including (1) breakup of the crust due either to a volume-expanding phase change in the mantle (Mutch and Saunders, 1976, p.51-53) or to mantle convection (Wise and others, 1979) and (2) impact by an asteroid-size body (Wilhelms and Squyres, 1984).

Following formation of the northern plains, Tharsis tectonism revived in Amazonian time, but at much lower intensity causing sporadic faulting in parts of the ridged plains material and plateau sequence rocks and in the Tharsis Montes, Medusae Fossae, Alba Patera, Arcadia, Tempe Terra, and Olympus Mons Formations. Late-stage calderas and concentric grabens formed on many of the Tharsis volcanic structures. Gravity studies suggest that the Tharsis swell is at least partly compensated at present (Phillips and others, 1973). Complete isostatic compensation of Tharsis at great depth has been simulated by crustal-thickness and mantel-density models (Sleep and Phillips, 1979).

Other structural features occur locally in the western equatorial region. Ancient impact basins are mostly buried and highly degraded but have exerted structural and topographic control on channels, ridges, linear depressions, and perhaps on other features (Schultz and others, 1982). Relatively recent vertical faulting and expansion within the Valles Marineris canyon system have offset canyon-wall and -floor materials (Blasius and others, 1977). The scarp (indicated by fault symbols) along the north edge of Argyre Planitia probably formed during or soon after the impact that formed this basin. Such scarps that encircle impact basins are common on the Moon. Origin of the basal scarp of Olympus Mons is controversial; hypotheses include deep-seated vertical tectonism (Mutch and others, 1976, p. 189–190) and landslide scars (Lopes and others, 1980).

GEOLOGIC SUMMARY

1. Early Noachian—High meteorite flux and intense bombardment of Martian surface; rugged basement rocks, mountains, and Argyre impact basin Planitia formed, northern lowlands developed by processes yet unknown.
2. Middle Noachian—Decreasing impact rate; emplacement of volcanic and impact-breccia plateau material; extensive faulting formed Claritas, Coracis, Acheron, Melas, and Nectaris Fossae.
3. Late Noachian—Widespread resurfacing and intercrater filling partly subdued older surfaces; formation of large ridges in Terra Sirenum and Noachis Terra; faulting radial to Syria Planum formed Ceraunius, Tempe, Mareotis, and Noctis Fossae; highland surfaces channelled and etched.

4. Early Hesperian—Eruption of lava flows (later ridged) in intercrater and lowland plains and in Lunae Planum; long, tongue-shaped lava flows emplaced east of Alba Patera and at Tempe Terra; faulting and rifting dominantly radial to Syria Planum-Pavonis Mons formed Valles Marineris and Ulysses, Memnonia, Sirenum, Icaria, Thaumasia, and Fortuna Fossae; widespread degradation and burial of most older cratered terrain by lava flows in lowland region.

5. Late Hesperian—Extensive lava flows erupted from sources at Tharsis Montes, Alba Patera, Ceraunius Fossae, Tempe Terra, and Syria Planum; deposition of layered material in chasmata; emplacement of lavas or sediments in northern Acidalia and Arcadia Planitiae; faulting of Noctis Labyrinthus; formation of chaotic terrain and large outflow channels north and east of Valles Marineris, extending into flood plains in Chryse Planitia and in southern Acidalia Planitia.

6. Early Amazonian—Extrusion of younger lava flows on and surrounding the Tharsis Montes and Alba Patera and in lowlands of Amazonis, Arcadia, and Acidalia Planitiae; formation of oldest Olympus Mons aureoles.

7. Middle Amazonian—Flows emplaced around Tharsis Montes; eruption of lavas continued in Amazonis Planitia; deposition of soft-appearing material in the Memnonia Sulci and Gordii Dorsum areas.

8. Late Amazonian—Ribbed debris aprons formed on northwest flanks of the Tharsis Montes and Olympus Mons, accompanied by minor volcanism; channel deposits in western Amazonis Planitia; deposition of plains material in Arcadia Planitia; deposition of soft material continued in Medusae Fossae and Amazonis Sulci areas.

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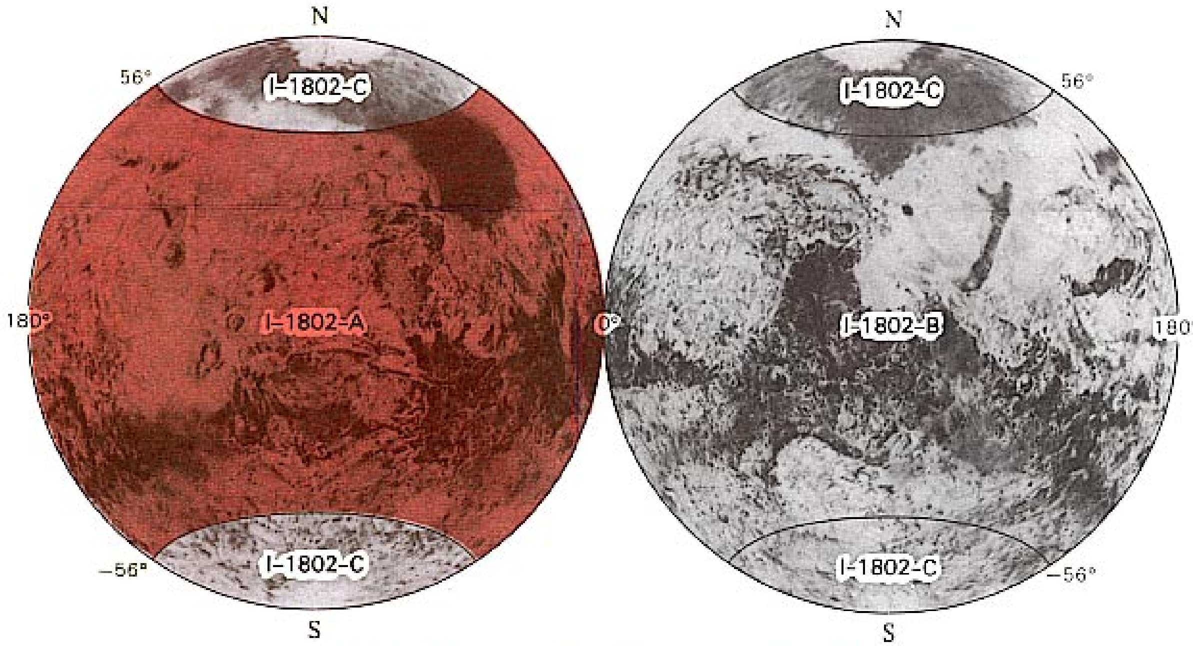

INDEX OF THE 1:15,000,000 GEOLOGIC SERIES

NOTES ON BASE

This map sheet is one of a series covering the entire surface of Mars at a scale of 1:15,000,000. Sources for the map base were 1:5,000,000-scale shaded relief maps described by Batson and others (1979). Data used in the map portrayal were obtained from Viking Orbiter images.

ADOPTED FIGURE

The figure of Mars used for computing the map projections is an oblate spheroid (flattening of 1/192) with an equatorial radius of 3,393.4 km and a polar radius of 3,375.7 km.

PROJECTIONS

The Mercator projection is used between the 57° parallels; the Polar Stereographic projection is used for the polar regions north and south of the 55° parallels. Scales are 1:15,000,000 at the equator and 1:9,203,425 at the poles. The projections have a common scale of 1:8,418,000 at lat ±56°. Longitude increases to the west in accordance with astronomical convention for Mars. Latitudes are areographic.

CONTROL

Planimetric control for the 1:5,000,000-scale maps used to compile the bases for these sheets was derived from photogrammetric triangulations by use of Mariner 9 pictures (Davies, 1973). This control net was upgraded through the use of Viking data (Davies and others, 1978). At least 85 percent of the image control points lie within 0.5 mm of the positions published in 1978.

MAPPING TECHNIQUE

The mapping bases for this series were assembled from 1:5,000,000-scale shaded relief maps reduced and digitally transformed where necessary to fit the projections. During shaded relief portrayal, features on these bases were used to position details taken from Viking Orbiter pictures. Features were drawn as if illuminated uniformly from the west, through use of airbrush techniques described by Inge (1972) and photointerpretive methods described by Inge and Bridges (1976). The shading is not generalized and accurately represents the character of surface features.

Shaded relief analysis and portrayal were made by Barbara J. Hall.

NOMENCLATURE

All names on this sheet are approved by the International Astronomical Union (IAU, 1974, 1977, 1980, 1983, and 1986). Named features and their positions are taken from published maps of Mars that have scales of 1:2,000,000, 1:5,000,000, and 1:25,000,000.

M 15M 0/90 G	Abbreviation for Mars; 1:15,000,000 series; center of map, lat 0°, long 90°; geologic map, (G).

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